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# INVESTIGATION OF LARGE EARTHQUAKE TRIGGERING ASSOCIATED WITH NON-VOLCANIC TREMOR ACTIVITY AT PARKFIELD, CA

Principal investigator, author:
**Robert M. Nadeau**
Berkeley Seismological Laboratory
215 McCone Hall,
University of California
Berkeley, CA 94720-4760
Tel: (510) 643-3980
Fax: (510) 643-5811
e-mail: nadeau@seismo.berkeley.edu

Recipient:
**University of California - Berkeley**

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e-mail: nadeau@seismo.berkeley.edu


## ABSTRACT


Recently, observational data from local and regional seismic networks have revealed the existence of deep (20 to 40 km) non-volcanic tremor (NVT) activity along the San Andreas Fault (SAF) beneath Cholame, ~25 km southeast of Parkfield, CA. Prior to this discovery, NVT activity had only been observed at subducting plate boundaries in Japan and Cascadia. A significant association between changes in the rate of NVT activity in Japan with the occurrence of moderate to large earthquakes and a striking correlation between changes in tremor activity with deep slow slip events in Cascadia has led to the hypothesis that processes associated with NVT activity are closely linked to processes in the seismogenic zone and that increased activity may signal accelerated stressing of the seismogenic zone, possibly triggering larger events. In the Parkfield-Cholame area, seismicity rates also appear to correlate with changes in tremor activity, supporting this hypothesis. The occurrence of the 22 December 2003, M6.5 San Simeon and 28 September 2004, M6.0 Parkfield earthquakes in close proximity to the Parkfield-Cholame tremor zone has afforded the opportunity to test this hypothesis further by exploring the relationships between tremor activity leading up to and following these events. The objective of this research has been to carry out such an investigation by compiling a multi-year baseline catalog of NVT activity, characterizing its spatio-temporal evolution and comparing this evolution to changes in coulomb-stress and seismicity rates associated with the San Simeon and Parkfield mainshocks. To provide greater spatial and temporal resolution, continuous seismic data recorded by a number of seismic networks has been used in the analysis (i.e. the HRSN, NCSN, SCSN, BDSN and USArray broad-band stations). Relative to the San Simeon and Parkfield mainshocks we find that: 1) NVT rates increase significantly in the Cholame area following both events, despite coulomb stress changes of less than 0.1 bars, 2) the NVT increase following San Simeon occurred despite any seismicity rate increase, 3) elevated NVT rates are ongoing, persisting well beyond the decay of Parkfield aftershocks, 3) the NVT rate changes were roughly proportional to the coulomb stress changes caused by each event on the tremor zone, 4) an episode for fore-tremor occurred ~ 21 days before the Parkfield event, 4) following Parkfield a previously non-existent periodicity in tremor rate episodes began, 5) the period of these episodes is progressively increasing through time, and 6) a pocket of deep NVT with lower activity also exists ~ 60 km northwest of Cholame beneath Monarch Peak, CA.

# FINAL TECHNICAL REPORT:

## INVESTIGATION OF LARGE EARTHQUAKE TRIGGERING ASSOCIATED WITH NON-VOLCANIC TREMOR ACTIVITY AT PARKFIELD, CA

### Introduction

*Scientific Significance.* Recently, observational data from local and regional seismic networks have revealed the existence of deep (20 to 40 km) non-volcanic tremor (NVT) activity along the San Andreas Fault (SAF) beneath Cholame, ~ 25 southeast of Parkfield, CA (Nadeau and Dolenc, 2005). Prior to this discovery, NVT activity had only been observed at subducting plate boundaries in Japan (Obara, 2000) and Cascadia (Rogers and Dragert, 2003). A significant association between changes in the rate of NVT activity in Japan with the occurrence of moderate to large earthquakes and a striking correlation between changes in tremor activity with deep slow slip events in Cascadia has led to the hypothesis that processes associated with NVTs are closely linked to processes in the seismogenic zone and that increased NVT activity may signal accelerated stressing of the seismogenic zone, possibly triggering larger events (Rogers and Dragert, 2003). In the Parkfield-Cholame area, seismicity rates also appear to correlate with changes in tremor activity, supporting this hypothesis (Nadeau and Dolenc, 2005). The occurrence of the 22 December 2003, M6.5 San Simeon and 28 September 2004, M6.0 Parkfield earthquakes in close proximity to the Parkfield-Cholame tremor zone has afforded the opportunity to test this hypothesis further by exploring the relationships between tremor activity leading up to and following these events.

*Reducing losses from Earthquakes in the U.S.* Obtaining a better understanding of fault zone processes responsible for the generation of earthquakes in the U.S. is critical to reducing losses from their occurrence. The research on NVTs carried out under this project is arguably fundamental to this goal. Based on the proximity of NVTs to locked fault zones and the correlation in time of NVT and deformation transients in subduction zones, the importance of NVTs as indicators of slow slip events underlying locked zones has now been recognized, and the information obtained through this project greatly enhances our understanding of the process of strain accumulation and release during the earthquake cycle at subseismogenic depths and immediately underlying the locked Cholame segment of the SAF that has been recognized as having significant potential for rupturing in a large and possibly catastrophic event in California (WGCEP, 1995). Knowledge of the evolution of stress and strain during the earthquake cycle is essential for accurate estimates of earthquake recurrence times and rupture parameters which in turn are critical inputs for earthquake forecasting, fault rupture models, and ground motion and earthquake hazard estimation.

*Objective.* The objective of this research has been to investigate the possible relationship that the 22 December 2003, M6.5 San Simeon and 28 September 2004, M6.0 Parkfield mainshocks had with the activity rates of NVT in the Cholame, and greater Parkfield areas of California. To achieve this objective we have: 1) compiled a multi-year baseline catalog of NVT activity spanning the two mainshocks, 2) characterized the spatio-temporal evolution of this activity, and 3) compared this evolution to changes in coulomb-stress and seismicity rates in the Parkfield-Cholame NVT zone associated with the San Simeon and Parkfield mainshocks. To provide greater spatial and temporal resolution, continuous seismic data recorded by a number of seismic networks (i.e. the HRSN, NCSN, SCSN, BDSN and USArray broad-band stations) has also been used in the analysis.

*Findings.* Relative to the San Simeon and Parkfield mainshocks we find that: 1) NVT rates increase significantly in the Cholame area following both events, despite average coulomb stress changes of less than 0.1 bars, 2) the NVT increase following San Simeon occurred despite any seismicity rate increase, 3) elevated NVT rates are ongoing, persisting well beyond the decay of Parkfield aftershocks, 4) the NVT rate changes, averaged over 90 days, correlate with the level of coulomb stress changes in the tremor zone caused by each mainshock, 5) an episode for fore-tremor occurred ~ 21 days before the Parkfield event in the nearby Cholame NVT zone, 6) following Parkfield a previously non-existent periodicity in tremor rate episodes began, 7) the period of these episodes in early 2005 was ~ 50 days with periods progressively increasing by ~ 15 days/year to current (early 2008) periods of ~ 100 days, and 8) a pocket of deep NVT with lower activity also exists ~ 60 km northwest of Cholame beneath Monarch Peak, CA.

## Compilation of the Multi-Year Catalog and Spatio-Temporal Characterization

*Detection.* With the exception of results from initial studies of limited spatial and temporal coverage and aimed at discovering ambient and triggered tremor activity (Nadeau and Dolenc, 2005; Gomberg et al., 2008), comprehensive and consistent catalogs of NVT activity spanning the San Simeon and Parkfield earthquakes are essentially non-existent for the Parkfield-Cholame area. We created such a catalog as part of this project by processing continuous seismograms recorded between August 2001 (inclusive) to present (i.e., we are continuing to routinely expand the catalog with ongoing activity). The initial stage of catalog development requires the compilation of a catalog of NVT detections. Detections of NVTs for the Cholame-Parkfield region are carried out using twenty sample-per-second (sps) continuous data channels from 8 stations (yellow triangles, Figure 1) of the borehole High Resolution Seismic Network (HRSN) near Parkfield California. We found that detection sensitivity of the borehole sensors was generally on the order of 5 to 10 times greater than surface sensors from the short-period Northern California Seismic Network (NCSN) even when distances to the HRSN sensors was several 10s of kms greater than to the NCSN sensors.

The continuous HRSN data amplitudes are first normalized to account for instrument gain differences and then 3 to 8 Hz band-pass filtered (Figure 2). Two sps root mean squared (RMS) envelope seismograms of these data are then generated using a 201 sample (10 sec.) boxcar window (Figure 2). Diurnal variations in background noise levels corresponding to cultural activity can often exceed 300 % in the HRSN data. To compensate for this, daily background noise level corrections are applied to each of the RMS seismograms. Noise level corrections for each channel are determined empirically using a 28 day median average correction for each 0.5 second sample of the day, and the corrections are recalculated seasonally to help account for minor seasonal variations that take place.

Following the noise level corrections, RMS seismograms are normalized to the 10 percentile amplitude level for the day being processed. The median amplitudes among the 8 envelope seismograms for each 0.5 second sample are then used to form a time series of amplitude transients (i.e., summary envelope) for the Parkfield-Cholame area. Detections for potential NVTs are then made when summary envelope amplitudes remain 300 % above the 10% background level continuously for 3 minutes or longer. The total period of time each detection remained continuously above the 300% level (i.e., the detection duration) was also included as part of the detection catalog.

The pre-envelope 3 to 8 Hz filtered data were then visually inspected to discriminate between NVT signal and amplitude transient artifacts (Figure 2). The visual inspection requires temporal coherence of secondary amplitude fluctuations among several stations. It also identifies and excludes coherent non-NVT activity such as earthquake swarms, unusual cultural noise signals (e.g., the SAFOD deep drilling project at Parkfield), and occasional multi-station artifacts that can occur during routine network operations.

As a typical example, 1705 potential detections were made for the 2002-2007 period (inclusive), and approximately 7.8 % of these were excluded during the visual inspection, yielding 1577 NVT detections for the region. Also excluded from the analysis are data for the hours of the day following the 22 December 2003, M6.5 San Simeon and 28 September 2004, M6.0 Parkfield California mainshocks and for the entire two days following these events. This was necessary because data for these periods was dominated by amplitude transients from 1000s of frequently overlapping aftershock signals making accurate and unbiased NVT detections difficult. The total duration of the 1577 NVT detections for the 2002-2007 period was 8962 minutes, with the median and interquartile range of detection duration per event being 4.68 and 3.17 minutes respectively.

***<u>Detection Results.</u>*** In Figure 3, a multi-year summary of the NVT activity rate history based on our detection catalog is shown using 1, 7, 30 and 90 day smoothing windows. Immediately apparent are the short and longer term increases in NVT rates following the San Simeon (SS) and Parkfield (PF) mainshocks. After an initial decay period following PF, NVT rates also remain elevated above pre-SS levels up to present (3+ years following PF), and a systematic pattern of previously non-existent quasi-periodic episodes of NVT activity has emerged with periods progressively increasing from an initial ~50 day period to an ~100 day period by early 2008 (not shown). Also apparent in the 1 and 7 day smoothing panels is a strong episode of NVT preceding the PF mainshock by ~ 21 days (i.e., foretremor). In the 90-day smoothed history another broader scale periodicity of ~ 300 days also appears to underlie the shorter term periodicity pattern.

*<u>Location.</u>* NVT locations in previous studies have been limited spatially and temporally to regions in the immediate Cholame region (Nadeau and Dolenc, 2005) or to tremors triggered by large teleseismic events (Gomberg et al., 2008). Furthermore, location accuracy and completeness has, in the past, been hampered by the limited number of stations that had the readily available continuous seismic records needed for determining the arrival times needed for locations. Since the beginning of 2006, however, the USGS and the Northern California Earthquake Data Center (NCEDC) have been making on-line continuous data available for all NCSN (NC) stations in the Parkfield-Cholame area (Figure 1). In combination with these data, we used continuous data from the HRSN (BP) and broad-band SCSN (CI), BDSN (BK), and USArray (TA) networks (Figure 1) to determine relative arrival time data between station pairs using envelope cross-correlation methods (Figure 2) to more accurately locate our detected tremors. In all, continuous data from 70 stations (potentially 2415 station pairs) was generally available for the 2006+ period, providing reasonably good coverage (Figure 1). However for most of the tremors in our study region, where tremors are very small by subduction zone standards, signal to noise issues were a significant problem and the typical number of stations used for locations was between 30 and 35. Nonetheless, even this smaller number of stations

provided a vast improvement on the coverage previously available, and by taking extra care in identifying and removing outliers and by using double-difference methods (HypoDD, Waldhauser, 2001) with a reference set of 50 good locations for constraints we were able to locate most (~80%) of the NVTs with good relative accuracy as determined from bootstrap and jackknife statistics (0.6-0.7 km horizontally; 1.0-1.2 km in depth) (Figure 4).

***Location Results.*** Our locations results (Figures 1, 4 and 5) for the 2006-2007 period are consistent the locations in the previous studies. They are also complete in their spatial and temporal coverage within the study region and time period. The improved completeness indicates that ~ 90 to 95% of ambient NVTs in the region are located exclusively in the Cholame area, with another ~ 5 % occurring in a pocket of activity ~ 60 km northwest of Cholame in the Monarch Peak area along the SAF (Figures 1 and 5).

**Comparison to Coulomb-Stress and Seismicity Rates**

Shown in Figure 5 are the 30 day smoothed histories for NVT activity and seismicity, and coulomb-stress maps for the San Simeon and Parkfield earthquakes. NVT activity in gray is for the entire detection catalog, while that in green for the subset of NVTs that were locatable and in the 50 x 50 km box encompassing the Cholame NVT zone, showing that the Cholame zone history is nearly the same as the detection catalog's. The seismicity history is also for only those quakes occurring in the same 50 x 50 km box. In comparing the NVT and seismicity rates, one sees that there is essentially no seismicity rate change associated with the distant San Simeon event, however, for the NVTs there is a significant increase. Coulomb stress changes from San Simeon at the NVT location and at 20 km depth were of the order of 0.046 bars, while at earthquake depths the value is about twice this (i.e.,, 0.10 bars). This suggests that NVTs may be sensitive to very small stress changes in the Cholame area and that they are significantly more sensitive to stress than earthquakes.

Coulomb stress changes in the NVT and earthquake zones following the Parkfield event are notably larger, being 0.073 bars in the NVT zone and 0.55 bars in the earthquake zone. At this higher stress change level, both the NVTs and earthquakes show a strong response. The NVT rate increase is also much larger than that following San Simeon. This indicates that the level of NVT response to stress change correlates with the level of stress change. The NVT rates have persisted for over 3 years following Parkfield, well beyond the elevated seismicity rate in the region. Also following Parkfield, quasi-periodic episodes of NVT activity have evolved which are not apparent in the seismicity rate data. These observations suggest that not only did the NVT zone respond in a decay like fashion following Parkfield, but they also appear to have been kicked into a new long-term state of elevated and episodic activity that is not reflected in the shallower seismicity. Because of the strong association with fault zone deformation with tremor activity seen in subduction zones and the greater sensitivity of NVTs to stress change, this may indicate that in the deep fault zone underlying the seismogenic fault, the mode of strain accumulation may have entered a new phase since the San Simeon and Parkfield earthquakes. Furthermore, the increase in NVT rates in this new phase may be signaling an increased rate of strain accumulation on the adjacent locked Cholame segment of the San Andreas fault.

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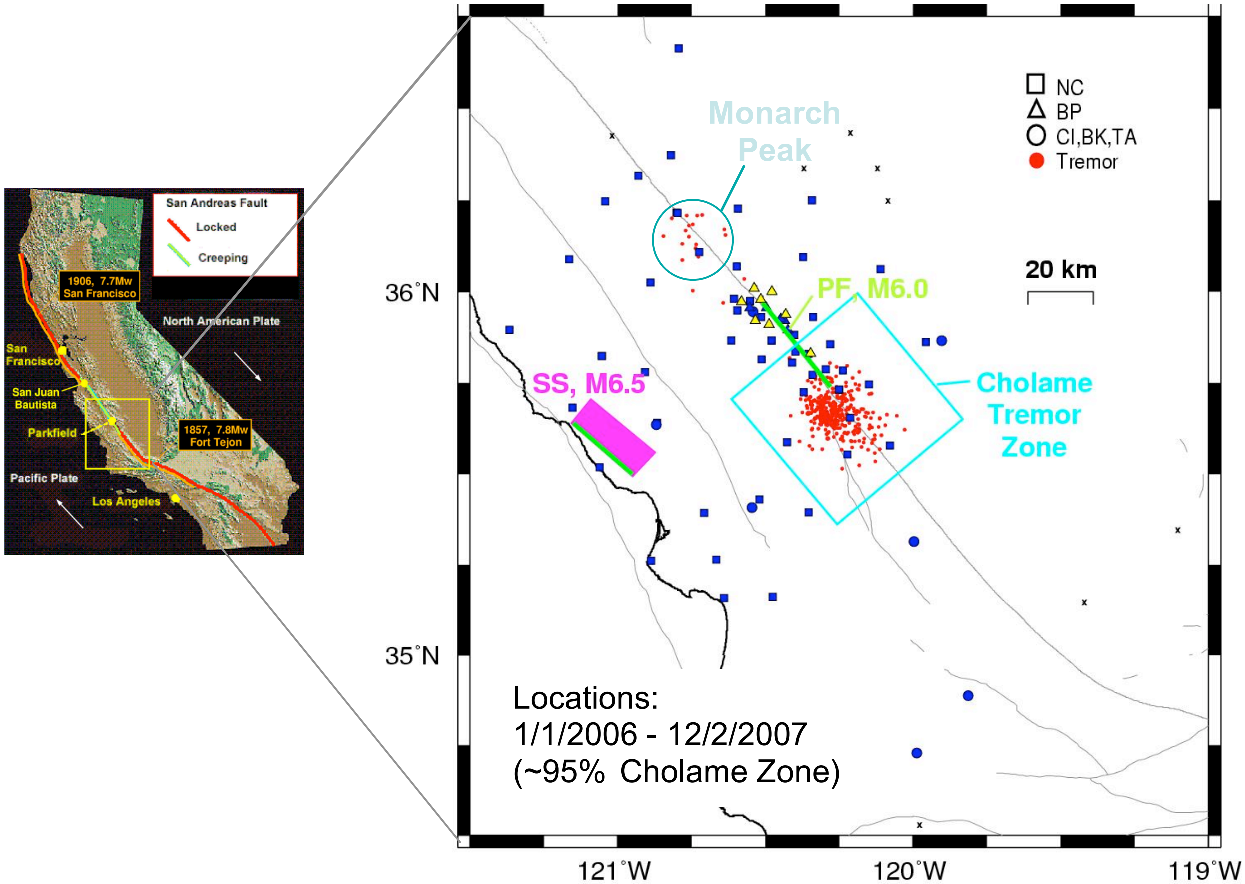
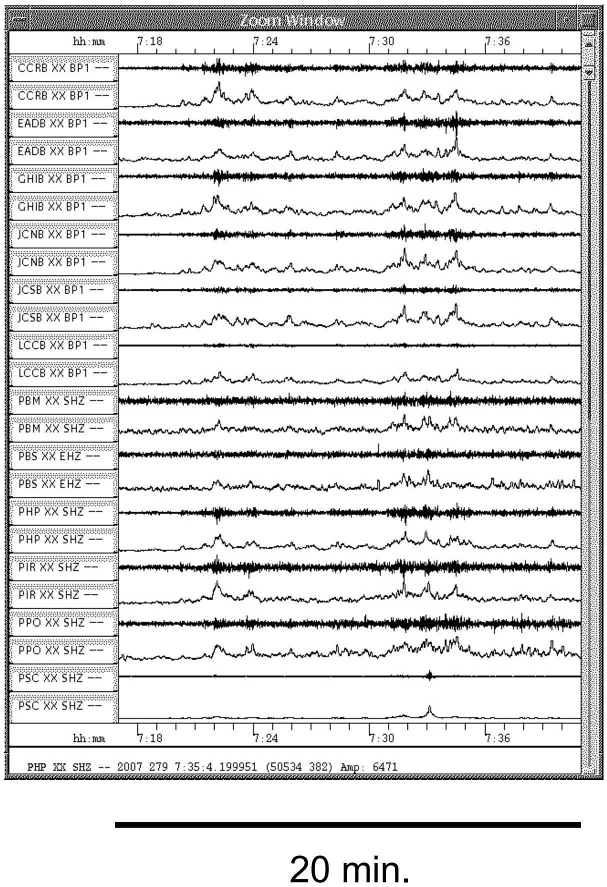



Figure 1. Map showing the study region, 2006-2007 tremor locations, stations used for the locations, and the San Simeon (SS) and Parkfield (PF) rupture zones. Yellow triangles are the 8 HRSN borehole stations used for detection. Ninety to Ninety-five % of the tremors occurred in the Cholame tremor zone for this period. About 5 % occurred in the Monarch Peak area. These locations are consistent those from the less spatially and temporally comprehensive studies for the region. The more comprehensive search undertaken by this project indicates that few tremors are located outside of these two regions.

## DATA / TECHNIQUES




**Envelope Based Detection / Alignment:**

- Largely Automated
- Continuous seismic data
- ~70, Stations;  5, Networks
- 20 sps
- 3-8 Hz bandpass
- 10 sec. RMS boxcar smoothed

**Detections:**

- 8 borehole stations (HRSN)
- Median station stack
- x3 S/N continuously for >= 3 min.
- Visual confirmation
- 1778 detections Aug. 2001 – May 2008

**Time Alignment:**

- Station-pairs
- Cross-correlation (time-domain)
- 6 min. window
- Quality control:
  + max. coef. >= 0.7
  + consistency (station-triplets)
- Least-squares inversion and detection time --> arrival times for location.

Figure 2. A sample of 3-8 Hz filtered seismograms and RMS envelopes for a moderate sized tremor. Detection requires that envelope amplitudes remain elevated above background levels for 3 or more minutes and that envelope shapes at the stations are similar (i.e., typically having maximum cross-correlations between station pairs of > 0.7). Relative arrival times among the stations for a tremor are obtained by determining cross-correlation delay times between station pairs and then performing a least squares inversion for all station pairs simultaneously.

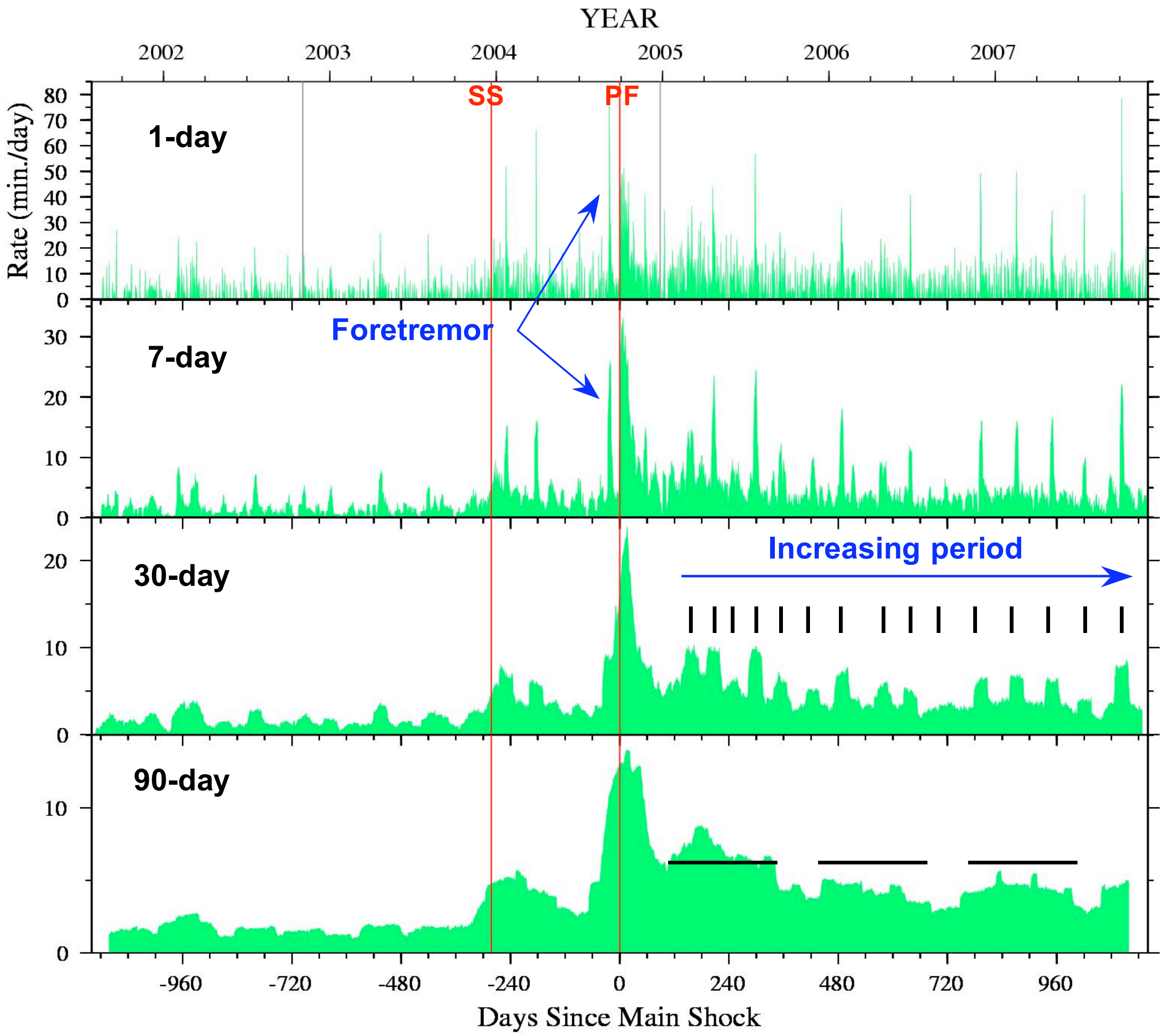
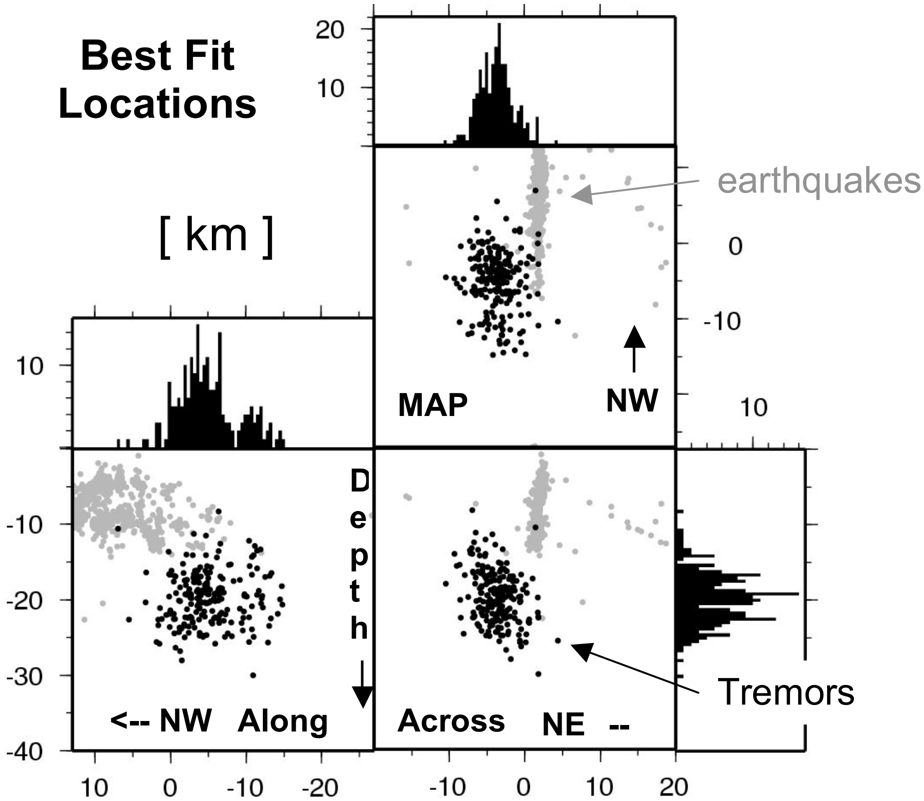



Figure 3. Time history of tremor activity using 1, 7, 30 and 90 day boxcar smoothing windows. Values are given as the average number of minutes per day of activity based on the durations from the detection catalog. SS and PF are times of the San Simeon M6.5 and Parkfield M6.0 earthquakes, respectively. Foretremor are unusually large episodes of activity preceding the Parkfield event. Black vertical dashes in 30-day panel are our interpretation of the approximate times of quasi-periodic episodes of tremor that evolved following the Parkfield event. Horizontal black bars indicate an apparent longer-term pattern ~ 300 day rate variations.



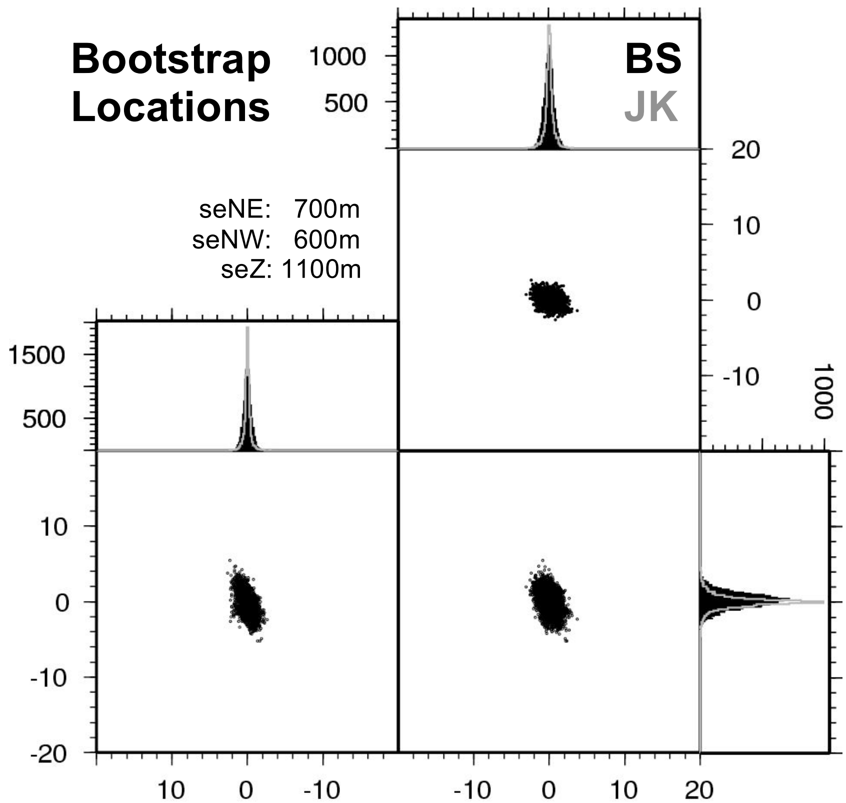




Figure 4. (Top) Map and along and across fault sections of tremor (black) and earthquake (gray) locations in the Cholame tremor zone. Histograms of the locations in each coordinate direction are also shown. (Bottom) Panels showing the distributions of perturbed bootstrap locations for the same sections as above. Also shown are histograms for both the bootstrap and jackknife perturbed locations. The perturbed locations (over 25,000 of them) show that the relative location standard errors are on the order of about +/- 1 km or better in each of the coordinated directions.

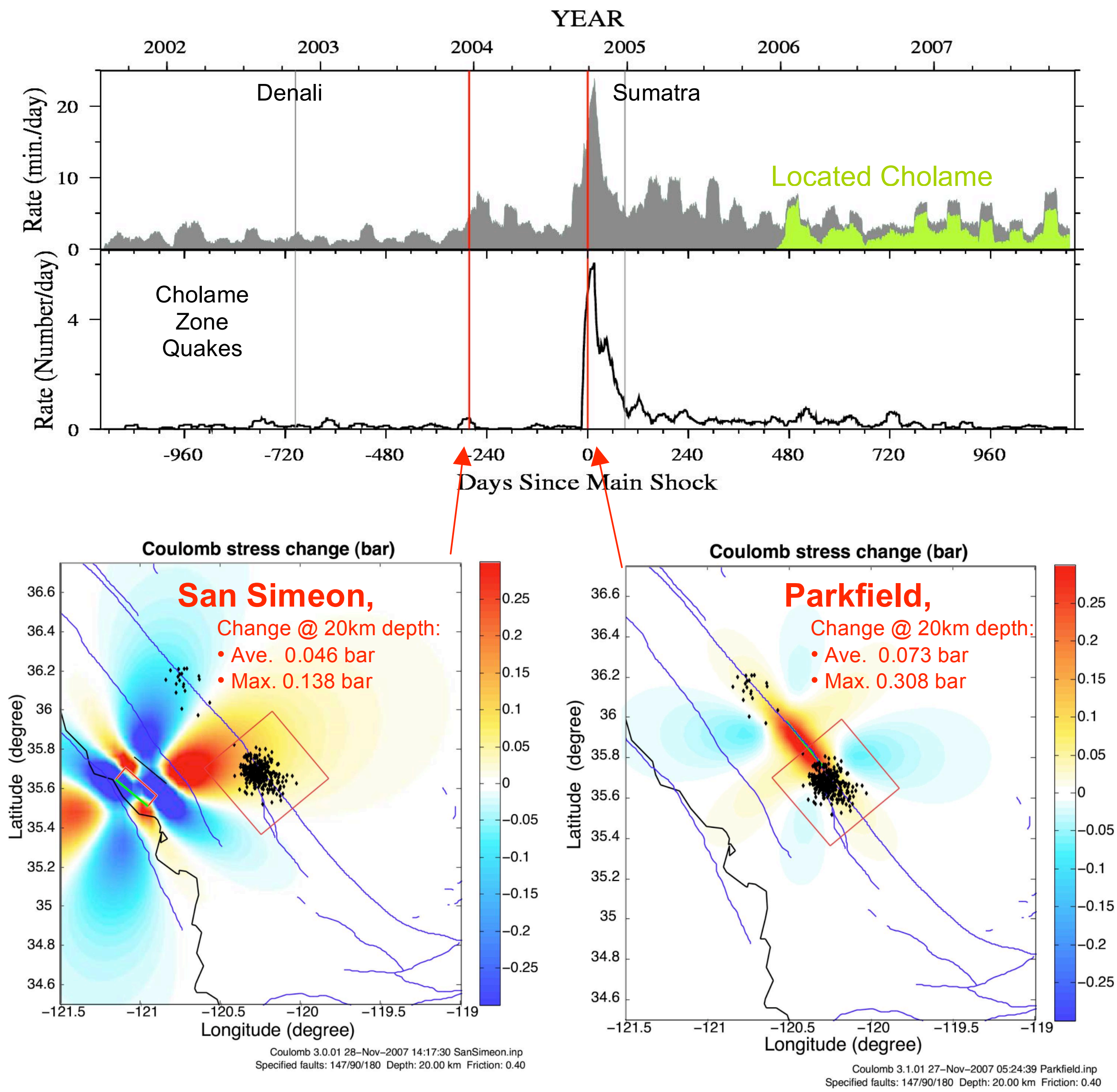



Figure 5. Comparison of tremor and earthquake rate evolution during the study period and their relationship to the coulomb stress changes from the San Simeon and Parkfield mainshocks. Also shown are the times of the teleseismic Denali and Sumatra events which also triggered tremor in the area. All tremor activity fulfilling the criteria set out in the text (including teleseismically triggered tremor) are represented in the rate histories.